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AUTHOR(S):

Matsuoka, Yuzuru

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How much should we reduce greenhouse gas emissions in order to combat the global warming problem?

YUZURU MATSUOKA

Abstract: Climate stabilization is one of the most serious problems that humanity faces this century. National climate policies in some European countries consider an increase of 2°C in the global mean temperature on that of the pre-industrial era to be a level of dangerous climate change. These countries have established action plans for the next 50 years in order to avoid overshooting this target. I reviewed the research on dangerous levels of climate change and analyzed the required reduction rates for greenhouse gas emissions. Based on this review, I discuss the required counter-measures and their feasibilities in order to overcome the global warming problem and to get through the first half of this century.

Keywords: global warming, climate stabilization, greenhouse gases, carbon dioxide.

Introduction

In the 1990s, the science of climate change developed rapidly and much new knowledge was gained. Many views have been expressed regarding the causes of climate change, but it has now been confirmed that greenhouse gases, primarily those resulting from human activity, are a major contributing factor. Future projections based on this knowledge have also been announced and climate change is predicted to have a serious negative effect on the world in the future.

The UK, France and other European nations have announced plans to reduce greenhouse gas emissions by 45-80% by 2050 based on their projections. Under the Kyoto Protocol to the United Nations Framework Convention on Climate Change (popularly known as simply the Kyoto Protocol), the UK is required to reduce greenhouse gas emissions by 12.5%, while France has a reduction target of ±0%. Compared with these Kyoto Protocol agreed levels, the new targets represent major reductions. In order to achieve these targets, major reform of the energy supply system and energy efficiency will be needed, in addition to major lifestyle changes on the part of the general public. The objective of this article is to identify the level of dangerous climate change, to determine the relationship between this level and the reduction targets and to discuss their feasibility.

Long-term targets and CO_2 reduction programs in the climate policy of European nations

Before the Kyoto Conference of 1997, the European Union proposed the following targets for long-term climate stabilization:

- Limiting the CO_2 concentration in the atmosphere to 550 parts per million (ppm).
- Limiting temperature rise to within 2°C above pre-industrial levels.

Subsequently, each of the plans put forward recently by European nations used these targets as a reference. Table 1 shows the targets of individual European nations. The UK and France have established CO_2 concentration objectives of 550 ppm and 450 ppm respectively, and both have established their own CO_2 reduction targets based on these objectives. The assessment procedure is as follows:

1. Determine the worldwide emissions that will enable the target for atmospheric CO_2 concentration to be achieved.
2. Assume that the per capita emissions in every country in the world will be the same.
3. Calculate an emission level that will not be exceeded after a certain year in the future.

For example, the UK plan assumes that the world population and economy will change according to the SRES A2 scenario (IPCC 2000), and national CO_2 emissions are calculated so that per capita emissions in the nation will be equal to the worldwide average emission allowance after 2050.

Climate change levels and impact

The level at which climate change must be stabilized depends on the estimated degree of the impact of climate change. In the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), released in 2001 (IPCC 2001b), five reasons for concern were raised regarding the impact of global warming, and the extent of the average global temperature rise predicted to have a major impact was reported on from these five perspectives. The first concern was the impact on unique

Table 1 Long term targets of national climate plans

Country	Status	Base year	Target year	Target gases	Reduction target	Notes	
France	National Climate Plan (2003), Factor 4 Program (2004)	2000	2050	Kyoto gases	75%	50% reduction of global emissions	75% reduction of GHG emissions by 2050 from 2000 level
Germany	Coalition agreement, part of German sustainability strategy.	1990	2020	GHG	40%		40% reduction of GHG emissions from 1990. in case of 30% reduction
	Parliamentary Enquete Commission (1990, 1998, 2002)	1990	2050	GHG	80%	Not exceed 2°Cabove pre-industrial level, below CO_2 450ppm	80% reduction of GHG emissions by 2050, from 1990 level
UK	DEFRA paper (2004), Royal Commision on Environmental Pollution (RCEP)	Current (2002)	2050	CO_2	60%	Below 550ppm CO_2 concentration	20% CO_2 emission reduction by 2010, 60% reduction by 2050, from 1990 level
Netherlands	Fourth National Environmental Policy Plan (VROM), Speech by NL environment minister	1990	2030	Kyoto gases	40～60%	30% reduction of global emissions from 1990 level	40～60% Kyoto gas reductions by 2030
Sweden	Swedish sustainability plan (2003)	1990	2050	Kyoto gases	50%	Below 550ppm Kyoto gases	Per capita emissions 4.5tCO_2eq (1.23tCeq) in 2050
Czech Republic	National climate change plan (2004)	2000	2020	CO_2	30% (43% of 1990)		40% reduction of per capita emission by 2030
EU	EU council meeting (1996)					Not exceed 2°Cabove pre-industrial level, below CO_2 550ppm	
	EU council meeting, 6th EAP, 2002			Kyoto gases		Not exceed 2°Cabove pre-industrial level, below 550 ppm Kyoto gases	
	EU Council meeting (2005), European Council (2005)	1990	2020	Kyoto gases	15～30%	Not exceed 2°Cabove pre-industrial level	Developed countries
		1990	2050	Kyoto gases	60～80%		

and threatened ecosystems that are already feeling the effects of climate change. Examples include the impact on semi-arid regions that constitute marginal regions for agriculture, such as the Sahel regions of West Africa, as well as regions that have experienced degradation of coastal wetlands, coral bleaching and coral death. With regard to these phenomena, even a temperature increase of approximately 1°C would have a serious impact. The second concern was extreme climate events – the increase in the number of floods, typhoons, heat waves and so on. An increase of approximately 1.5°C in the average global temperature would increase the risk to life, property, crops and ecosystems in areas such as coastal lowlands, river flood plains and so on, that are susceptible to extreme weather events. The uneven distribution of impacts provided the third reason for concern. A temperature rise of approximately 2-3°C would boost crop production in regions such as Russia and the Ukraine but would have a catastrophic effect on other regions. Whether the effects would occur locally or selectively in either developing or developed nations is also of great concern. The balance between developing and developed nations is a particularly difficult problem. The fourth area for concern is the global aggregate impact. This will be particularly great if the average global temperature should increase by more than 2-3°C. Finally, the fifth reason for concern is large-scale, irreversible and catastrophic events such as the shutdown of thermohaline circulation, the collapse of the West Antarctic ice sheet (WAIS), the mass extinction of forests and so on. The IPCC estimates that the threshold for the occurrence of such events is a temperature rise of approximately 5°C. Recent studies have estimated the threshold to be lower, at around 2-4°C. (Table 2)

The aforementioned EU proposal to limit the global temperature rise to within 2°C of pre-industrial levels uses the present temperature as a reference point in proposing a permissible temperature rise target of 1.4°C (2°C minus the temperature rise to date, which stands at 0.6 °C on pre-industrial levels). Accordingly, this value is equivalent to a target set mainly from the standpoint of reasons for concern two through to five listed above. With regard to the first reason for concern, it goes without saying that it would be most desirable to avoid posing any danger to those unique ecosystems already threatened by the impact of climate change. However, as will be discussed later, even a target of 2°C represents an enormous value that will necessitate vast reductions in greenhouse gas emissions. Achieving this target will require not only a drastic transformation in the system of energy supply and demand but great changes in socioeconomic systems as well. Considering the relationship between such climate stabilization targets and the difficulties involved in climate mitigation policy, it is necessary to study the relevant factors and set a target that is not only feasible but also ensures a low risk of impact from climate change.

Table 2 Levels of dangerous / not dangerous climate change

	Levels of dangerous / not dangerous climate change	Notes
1987	Speed of temperature rise＜0.1℃/decade, speed of SLR＜2～3 cm/decade. Estimation with species change of natural ecosystems, maximum moving speed of forests and social infrastructures.	WMO/UNEP (1988) *A summary of the discussions and recommendations of the workshops held in Villach(1987) and Bellagio(1987)*, WCIP-1, WMO/TD-No.225, 53pp.
1988	Temperature rise＜2℃, Speed of temperature rise＜0.03℃／decade.	Sassin, W., Jaeger,J., di Primio, J.C. and Fisher,W., (1988) *The Climate Problem between Science and Politics,* KFA Juelich. UNEP/Beijer Institute (1989) *The Full Range of Responses to Anticipated Climatic Change*, United Nations Environment Programme GEMS and The Beijer Institute, 182p.
1989	Speed of SLR＜1～2cm／decade.	Park, R.A., Trehan,M.S., Mausel,P.W. and Howe,R.C. (1989) The effects of sea level rise on U.S. coastal wetlands, in *Potential Effects of Global Climate Change on the United States,* U.S. EPA, Washington D.C.
1990	Low risk: temperature rise＜1℃, high risk: >2℃. Speed of temperature rise＜0.1℃／decade. SLR＜0.2～0.5m, speed of SLR ＜20～50mm／decade.	Rijsberman, F.R. and Swart, R.J., 1990, *Targets and Indicators of Climatic Change*, The Stockholm Environmental Institute, 166p.
1995	Temperature rise＜1～2℃ from pre-industrial era, speed ＜0.2℃／decade.	WBGU (1995) *Scenario for the derivation of global CO2 reduction targets and implementation strategies.* Statement on the occasion of the First Conference of the Parties to the Framework Convention on Climate Change in Berlin. Bremerhaven.
1996	Temperature rise＜1～2℃, speed＜0.1～0.2℃／decade, SLR＜20～40cm, reduction of CO2 emission＜2～4%／year.	Alcamo, J and Kreileman, E. (1996) *Background Report prepared for the Workshop on Quantified Emission Limitation Reduction Objectives* at the Third Meeting of the Ad Hoc Group on the Berlin Mandate. Framework Convention on Climate Change. Geneva. 28 February.
1996	Temperature rise＜1～2℃, speed＜0.1～0.2℃／decade, SLR＜20～40cm, reduction of CO2 emission＜0.5～1.5%／year.	Matsuoka,Y., Morita,T. and Kawashima,Y. et al. (1996) *Background paper prepared for the Ad Hoc Group on the Berlin Mandate*, Framework Convention on Climate Change, Geneva, 8-19 July 1996
2001	Not intensify water shortage in vulnerable regions＜450～650ppm.	Parry, M., N. Arnell, T. McMichael et al. (2001) *Global Environmental Change (Part A)* 11(3), 181-183.
2001	Above 1℃ temperature increase, coral bleaching will occur globally.	Smith, J. B., Schellnhuber,H.-J. and Mirza, M.M.Q. (2001) in eds., J. J. McCarthy et al. *Climate Change 2001,* Cambridge: Cambridge University Press, 913-967.
2003	Tolerable limits of most natural ecosystems are 1～2℃.	Hare, W. (2003) *Background Report to the German Advisory Council on Global Change* (WBGU) Special Report 94.
2002	Risk of WAIS collapse is not small by 2℃ global temperature increase or 450ppm CO2. Risk of THC shutdown is not small by 3℃ global temperature increase within 100 years.	O'Neill, B. C. and Oppenheimer, M. (2002) *Science* 296 (5575) 1971-1972.
2004	Bad influence to economic sectors by 3～4℃ temperature rise.	Hitz, S. and Smith, J. (2004) *Global Environmental Change* 14(3): 201-218
2004	Shutdown of THC by 700ppm CO2.	Keller, K., Bolker, B. M. and Bradford, D. F. (2004) *Journal of Environmental Economics and Management.* 48(1), 723-741.
2004	WAIS collapse by 2～4℃ or 550ppmCO2.	Oppenheimer, M. and Alley, R.B. (2004) *Climatic Change* 64, 1-10.
2004	Risk of Greenland ice sheet collapse by 1℃ temperature increase.	Hansen, J. (2004) *Scientific American* 290(3), 68-77.
2004	50% of ecosystems can adapt 0.1℃／decade. 30% can adapt 0.3℃／decade, rapid degradation by 4℃／decade.	Leemans, R. and Eickhout,B. (2004) *Global Environmental Change (Part A)* 14, 219-228.

SLR: sea-level rise
WAIS: West Antarctic ice sheet
THC: thermohaline circulation

The relationship of atmospheric stabilization targets, temperature change and emissions

The ultimate objective of the United Nations Framework Convention on Climate Change signed at Rio de Janeiro in June 1992 is “the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” The Framework Convention elaborates: “Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.”

So what is the relationship between these targets for the stabilization of atmospheric concentrations, temperature change and the difficulty of emissions reductions? A model for calculating greenhouse gas emissions, the circulation of substances in the atmosphere and oceans and the accompanying climate change was used to study this relationship (Hijioka et al. 2005).

First, the target period for the analysis was set at 1990-2200, taking into consideration the time scale for a global thermal response. Emission reductions were planned so target concentrations for atmospheric stabilization would not be exceeded during this period. The climate sensitivity,[1] a value of long-term global

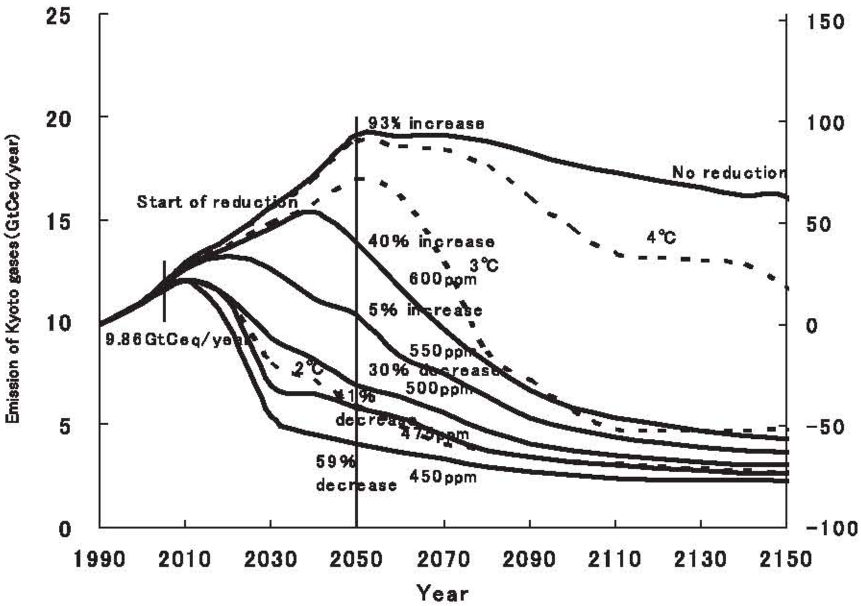

Fig. 1 Targets of climate change and emission of Kyoto gases

mean temperature change when the atmospheric CO_2 concentration is doubled, was set to 2.6°C, and the time preference[2] between present and future was set to 4% per year. Figure 1 shows the emissions of the six greenhouse gases listed in the Kyoto Protocol (hereafter "Kyoto gases")[3] for which the target concentration is 450-600 ppm and for which stabilization targets are not imposed. In the case of a target concentration of 450 ppm, drastic reductions (45% reduction as compared with 1990 levels by 2030) must be implemented immediately. In the case of a target concentration of 550 ppm, slight reductions (28% reduction as compared with 1990 levels by 2030) are needed, while a target concentration of 600 ppm represents a 48% increase as compared with 1990 levels by 2030. These target values are the equivalent values of CO_2 concentrations, which would cause the same amount of temperature change as *all* the main causes of climate change[4] (hereafter "RF equivalent concentration"). Since they include sulfate aerosols, organic carbons and other substances that have cooling effects, the values that convert only Kyoto gases into CO_2 concentrations (hereafter "Kyoto gas concentration") will be higher by several dozen ppm. Moreover, as the Kyoto gas concentrations include methane, nitrous oxide and other Kyoto gases in addition to CO_2, they will be higher than the CO_2 concentration alone by several ppm to several dozen ppm.

While the temperature will continue to rise throughout the entire period, the increase will be approximately 1.8°C for a target concentration of 450 ppm and 2.4°C for a target concentration of 550 ppm. Table 3 shows a comparison of these changes in temperature increase, organized by target concentration. As this table shows, the temperature increase as of the year 2150 for a target concentration of 475 pm will be 1.98°C, indicating that the target concentration corresponding to the 2°C target in the previous section is approximately 475 ppm.[5]

However, this relationship is greatly dependent on climate sensitivity. Table 3 shows the temperature changes for a climate sensitivity of 2.6°C, but the IPCC says that the range for climate sensitivity is 1.5-4.5°C, and some studies contend that the range is even greater. Figure 2 shows the probability that the rise in long-term, global average temperature will not exceed the target temperature rise when this uncertainty is taken into account and the target concentration is set to 450-600 ppm.[6] In short, for the 450 ppm target, the probability that the temperature rise will not exceed 2°C is approximately 64%, while for the 475 ppm target, the probability is approximately 51%, and for the 550 ppm target the probability is approximately 24%.

Table 3 Targets of climate change, atmospheric concentrations and emissions

(a) Temperature change and sea-level change

Target (ppm)	Temperature change (°C from pre-industrial era)				Sea level change (m from 1990)		
	1990	2050	2100	2150	2050	2100	2150
No reduction	0.60	1.98	3.53	4.45	0.11	0.25	0.40
RF equivalent concentration targets (include natural causes)							
450	0.60	1.56	1.75	1.78	0.09	0.15	0.20
475	0.60	1.70	1.94	1.98	0.10	0.16	0.22
500	0.60	1.80	2.12	2.17	0.10	0.18	0.23
550	0.60	1.88	2.44	2.52	0.10	0.20	0.26
600	0.60	1.90	2.71	2.84	0.10	0.21	0.29

(b) Atmospheric concentrations

Target (ppm)	RF equiv. concentration (ppm)			CO_2 concentration (ppm)			Kyoto gases (CO_2equiv.,ppm)		
	1990	2050	2100	1990	2050	2100	1990	2050	2100
No reduction	348.5	590.2	855.2	353.3	522.5	667.3	393.4	656.2	888.4
RF equivalent concentration targets (include natural causes)									
450	348.5	450.0	450.0	353.3	438.0	433.4	393.4	469.9	459.1
475	348.5	475.0	475.0	353.3	448.0	454.6	393.4	497.1	485.5
500	348.5	499.9	500.0	353.3	460.0	475.5	393.4	520.6	509.7
550	348.5	541.2	550.0	353.3	491.3	521.2	393.4	567.9	561.9
600	348.5	559.9	600.0	353.3	517.0	567.5	393.4	608.2	615.7

(C) Emissions

Target (ppm)	CO_2 emissions (GtC/year)				Kyoto gas emissions (GtCeq/year)				GHG emissions (GtCeq/year)			
	1990	2020	2050	2100	1990	2020	2050	2100	1990	2020	2050	2100
No reduction	7.10	10.00	13.81	12.70	9.86	14.11	19.11	17.68	11.86	14.27	19.13	17.69
RF equivalent concentration targets (include natural causes)												
450	7.10	8.38	2.95	1.70	9.86	9.87	4.02	2.54	11.86	10.03	4.04	2.55
475	7.10	8.38	4.33	2.32	9.86	11.11	5.84	3.16	11.86	11.26	5.86	3.18
500	7.10	8.38	5.12	2.89	9.86	11.23	6.90	3.73	11.86	11.38	6.92	3.75
550	7.10	10.00	7.93	3.93	9.86	13.26	10.34	4.76	11.86	13.41	10.36	4.78
600	7.10	10.00	11.13	4.97	9.86	13.58	13.84	5.81	11.86	13.74	13.86	5.83

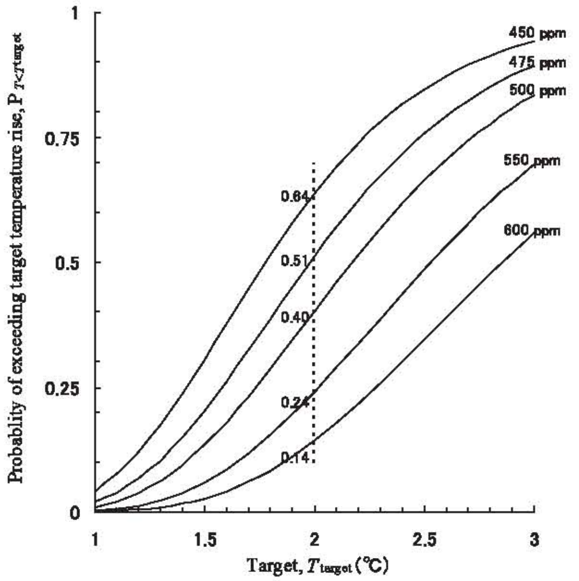

Fig. 2 Probability of exceeding target temperature rise

The path to sustainable development and climate stabilization

The emission paths leading to climate stabilization that are shown in Figure 1 – the model used to calculate these emission paths – are based on the economics-based approach promoted by Solow et al. (1974). This approach takes the Hicks-Lindahl concept as the base of economic development; it magnifies the flow of income and economic welfare attainable to the extent that it will not waste the stock of assets that produce income (atmospheric environment). In this concept, the environment is held to be one part of the capital that produces income, and priority is put on economic efficiency. The paper by Wigley, Richels and Edmonds that appeared in the January 1996 issue of *Nature* (Wigley et al. 1996) is well known for proposing emission paths based on such economic concepts and pointing out problems associated with these emission paths. In that paper, the authors conducted the same type of calculations as those shown in Figure 1 and pointed out that, if the aim was to stabilize the CO_2 atmospheric concentration at 550 ppm in the future, several routes were available that would enable CO_2 emissions to be reduced in this manner. The authors also asserted that, rather than immediately commencing reduction measures as recommended by the IPCC, emissions should instead be left to take their course until 2010 or 2020 and reduction measures introduced afterwards and all at once. This, they argued, would have lower economic costs. Their reasons were as follows:

- Setting the time preference to a comparatively large value and paying the costs in the future would be cheaper.
- Capital could be upgraded smoothly over a period of about 20 years.
- In the future, progress in technical innovation will lower the cost of technologies.

Wigley, Richels and Edmonds also concluded that since the change in temperature resulting from differences in these routes would be slight, there would be little difference in the degree of damage caused by global warming. As could be expected, there were many counter-arguments to the views expressed in their paper. Each of these counter-arguments focused on the essentials of the paper, criticizing such aspects as the fact that the time preference was set to a high value or the assumption that technical innovation would proceed spontaneously. The degree to which the settings for time preference and the speed of technological innovation alter the emissions reduction schedule shown in Figure 1 differs greatly depending on the target concentrations that are set. Figure 3, for example, shows emission paths when the value for time preference for targets of 475 ppm and 600 ppm is changed to 2, 3, 4 and 5% per year in order to view the effect of time preference. For the 475 ppm target, the emissions in 2020 will

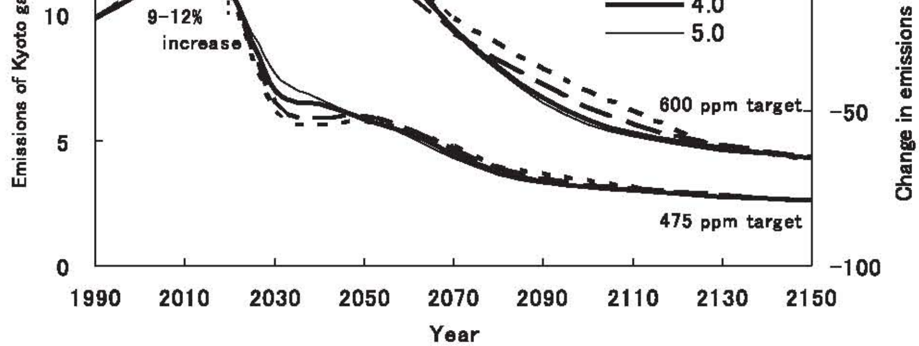

Fig. 3 Time preference and emission paths

vary narrowly between an increase of 9% (for a time preference of 2% per year) and 12% (for a time preference of 5% per year) on 1990 levels. However, for the 600 ppm target, the increase will be 31-40%. The effect of time preference on targets for CO_2 concentration varies considerably. It is also thought that the speed of technical progress, especially the speed of improvements in energy efficiency, will have a great effect on future emission paths. Figure 4 shows the results of a study conducted to determine the impact of these developments on emission paths. The figure shows the path when, for example, this value is varied within the range of 0.1-1.5% per year for a target of 475 ppm. In this case, the difference was relatively slight, with the increase as of 2020 varying between 12-15% compared with 1990 levels. In other words, the selection of time preference and the estimation of the speed of technical innovation will affect the emissions reduction schedule to some extent. However, for a severe target of 475 ppm (or 2°C), emissions in all cases must be reduced by approximately 40% of 1990 levels by around 2050. The result is not greatly changed by differences in the selection of time preference and the estimation of the speed of technical innovation.

Discussions such as that of the United Nations Framework Convention on Climate Change and of Wigley et al. (1996) define the level of dangerous climate change with atmospheric stabilization concentrations. However, since the speed of climate change in

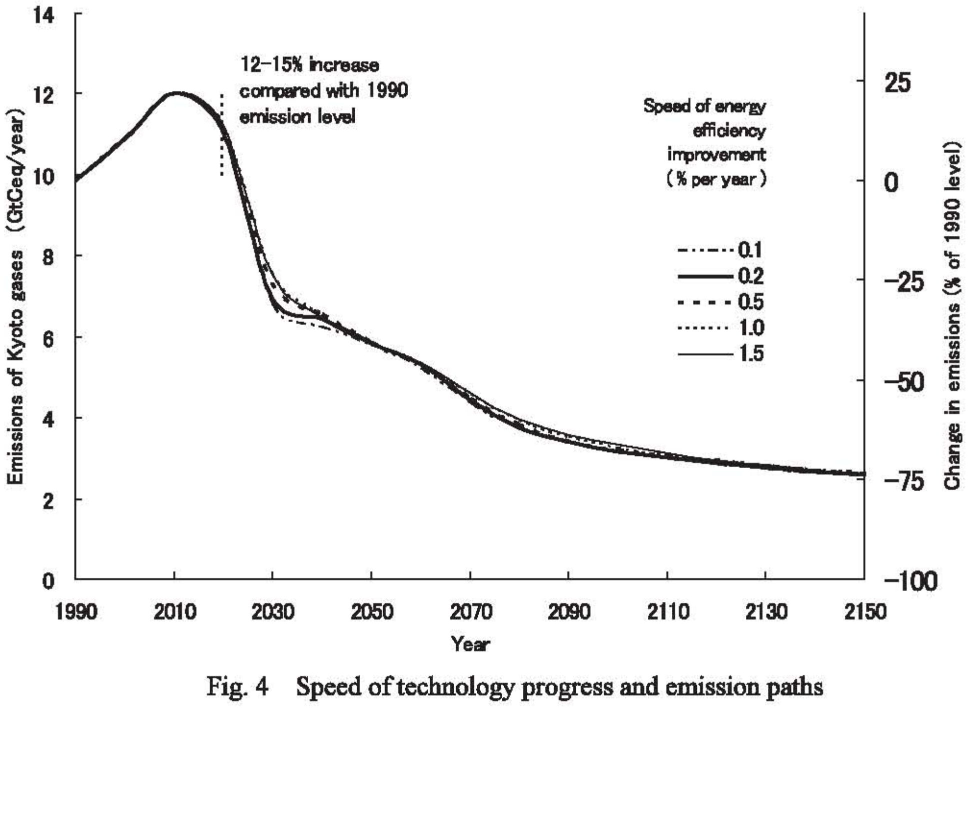

Fig. 4 Speed of technology progress and emission paths

general will vary even for the same target concentration, in other words, it depends on the emission path, it is possible that these variations will also determine the degree of adaptability of natural ecosystems or change the probability of the occurrence of unexpected phenomena such as ocean circulation changes. From this environmental capacity standpoint, discussions that focus on stabilization concentrations alone are inadequate, and attention must also be paid to the speed of climate change. The speed of climate change has been used as an indicator of dangerous climate change levels so far (Table 2). In discussions of emission allowance that took into account the speed of climate change (for example, Matsuoka 1998), the primary objective was to establish a "danger zone" on the two-dimensional plane of climate change speed and change quantity shown in Figure 5. The threshold for the danger level was determined based on knowledge such as past ecosystem response and the speed at which vegetation is able to adapt to climate fluctuations. In this, a temperature rise variation of 1-2°C and a change rate of approximately 0.1-0.2°C per decade were often used. Such change rate targets were determined from the adaptability of plant species and the speed of movement observed in the postglacial period and so on. These ranges are shown as the lightly shaded area in Figure 5. The solid line in Figure 5 is the path of temperature change given by the emission path shown in Figure 1; the points indicate the passing points every 10 years starting from 1990. For the 450 ppm target, the level goes slightly

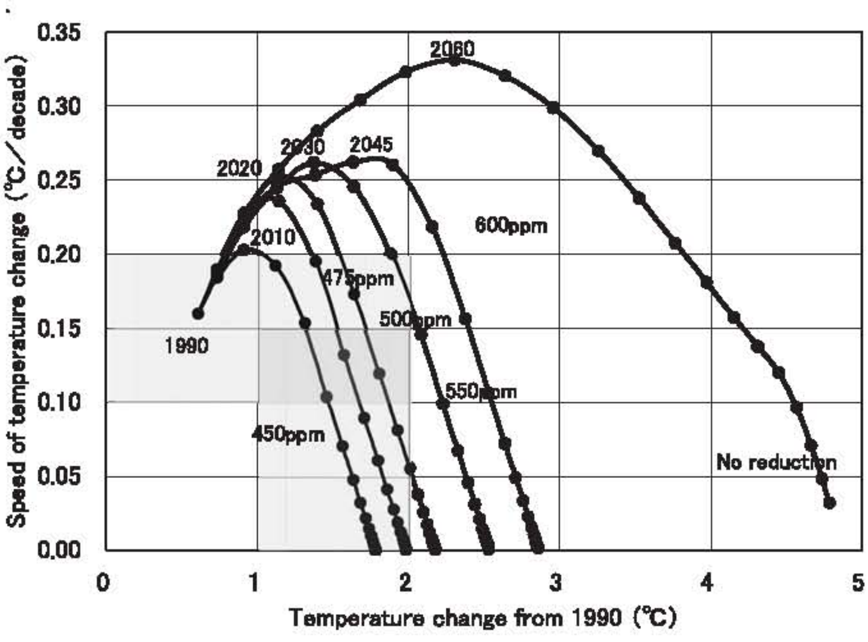

Fig. 5 Temperature change and speed of temperature change

outside the speed threshold around 2010, but it returns immediately to the shaded area. For the 475 ppm target, the level enters the danger zone before 2010 but returns to the shaded area around 2030. For the 600 ppm target, the level enters the danger zone and thereafter does not return to the shaded area.

There are advantages and disadvantages to this kind of discussion, in which the speed of climate change is used as an indicator of the danger level. First, the addition of the speed of climate change to the danger level indicators is more appropriate than a discussion of change levels alone. However, this approach involves much greater uncertainty than the discussion of change levels themselves. For example:

1. What value should be used for the speed threshold?
2. To what degree does the speed of global average temperature change represent a danger to individual regions?
3. How should we evaluate the diverse adaptability of global ecosystems to the speed of climate change?

This third point was also raised by Leemans and Eickhout (2004). In the light of all three uncertainties, we must say that serious problems remain when using the speed of change as an indicator of the danger level.

Reduction targets for Japan

Up to now, each of the studies has focused on global emission allowances. How should these global emissions be allocated to individual countries? This is the so-called burden share problem, and it is the subject of heated debate regarding equity, emission responsibility, reduction capacity and so on. In this debate, the Contraction and Convergence (C&C) approach proposed by Meyer (2000) shows clear equity in the sense that per capita emissions for every country in the world are identical after the convergence year; for this reason, this approach has been used in the aforementioned target-setting in the UK and France.

The C&C approach comprises three main points. The first is setting the years for when contraction is expected to begin and convergence finish. The second point is the reduction rule during the contraction period. The third point is the extent to which the trading of emission allowances is permitted among individual countries and regions. Since total global emissions will vary depending on the contraction method, the emission allowances following the convergence year will change as well. If reduction contraction is conducted so that total Kyoto gas emissions from all regions will become equal to the global emissions path shown in Figure 1, the regional emissions following the convergence year will be equal to the global emissions multiplied by the population ratio (regional population/world population). Table 4 shows the per capita emissions and necessary reduction rate during the convergence period assessed using this method for Japan, other developed nations (including countries in the former Soviet Union and Eastern Europe) and developing nations. As this table shows, the per capita emissions in 2050 is 0.43 tCeq / (person・year) for a target concentration of 450 ppm, 0.62 tCeq / (person・year) for a target concentration of 475 ppm, and 0.74 tCeq/ (person・year) for a target concentration of 500 ppm.

Emissions for Japan are equivalent to 12%, 18% and 21%, respectively compared with 1990 levels. To put it another way, the reduction rate needed in 2050 to reach a target of 475 ppm (equivalent to 2°C) is 100−18 = 82% compared with 1990 levels. This value is dependent on the population setting for 2050. 82% assumes a median value for the Japanese and world populations. When the population for Japan alone is changed to a high and a low value, the figure becomes 81% and 84%, respectively. In

Table 4 Target concentrations and allowable emissions

	Per capita emission (tCeq/(cap・year)	Emission (% of 1990) World	Japan	DC	LDC
Target 450 ppm					
2050	0.43	41	12	11	81
2100	0.24	26	4	6	52
Target 475 ppm					
2050	0.62	59	18	15	118
2100	0.30	26	6	7	65
Target 500 ppm					
2050	0.74	70	21	18	139
2100	0.36	38	7	8	77
Target 550 ppm					
2050	1.10	105	32	27	208
2100	0.46	48	8	11	98
Target 600 ppm					
2050	1.48	140	43	36	279
2100	0.56	59	10	13	120
Population assumption World: SRES B1 Japan: Estimation by NIPSSR, 2004					
1990		52.6	1.24	12.7	39.9
2050		93.7	1.01	13.8	79.8
2100		104.1	0.64	13.1	91.1

DC: developed countries

LDC: less developed countries (developing countries) all cases, a reduction rate of more than 80% is needed. When the same calculations are performed for the developing world, the results are an 18% (=118−100) increase over 1990 levels and a 41% (=100−59) reduction in per capita emissions. The necessary reduction rate decreases as the target concentration increases. For a target of 600 ppm (a temperature rise of just under 3°C), the reduction rate for Japan is 57% and the rate of increase for the developing world is 179%.

These calculations use the C&C approach and, when analyzing the results, it is necessary to have a clear understanding of the advantages and disadvantages of this method. The most important feature of this approach is that an equal per capita emissions allowance is provided for every country and region of the world, regardless of whether their current emissions are high or low. This is an extremely simple rule and in this sense it is both persuasive and equitable. However, it leaves major problems unresolved with regard to economic efficiency. Second, there is the problem of great inequity in terms of reduction burden. While the targets for developed countries are severe, some regions in the developing world will not reach their emission allowances for the next 50 years. Many revised proposals are currently being prepared to resolve these problems and further study that includes these proposals will be needed before this approach can be applied widely.

Feasibility of Japan's 80% reduction

As noted above, Kyoto gas emissions must be reduced by approximately 80% in the first half of this century to keep the increase in global mean temperature to 2°C or less on pre-industrial levels. European nations are drawing up plans to reduce emissions by 60-80% by 2050 and are therefore in line with this goal. In order for this goal to be achieved in the next 45 years (before 2050), a speed of transformation that is significantly faster than the pace of societal change will be needed. This section will focus on how this may be achieved, using Figure 6 for purposes of illustration.

For purposes of simplicity, I assume the target gas for reduction is limited to CO_2. Considering the increased emissions from 1990 to 2005, an 80% reduction on 1990 levels represents a reduction of approximately 82% on 2005 levels. In order to achieve the reduction in the next 45 years, a reduction speed of 3.7% per year or more will be needed. This will be shown as a ($<$ -3.7%, with a negative value indicating a decrease in emissions). An identity exists on the a.[7] The a is a sum of following changing rates; the rate of change in the ratio of carbon dioxide capture and storage[8] (b), the rate of change in carbon intensity (c), the rate of change in energy intensity (d), the rate of change in per capita economic activity (e), the rate of change in population (f), and the

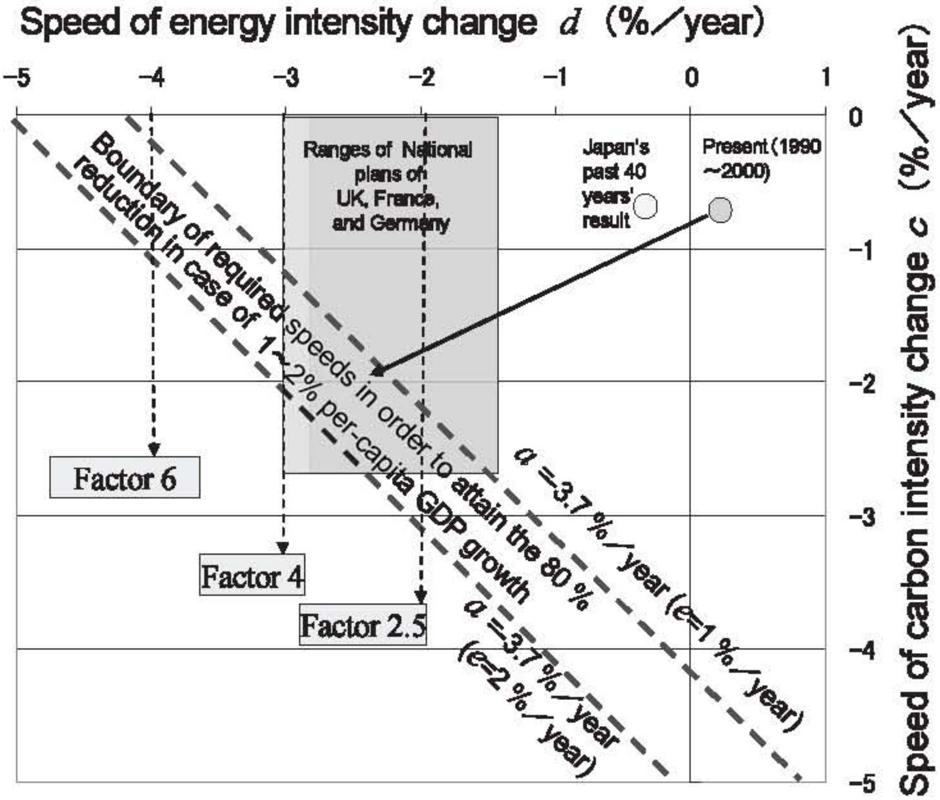

Fig. 6 Speeds required to reduce emissions by 80% by 2050 in Japan

confounding term (*g*). In this article, the national gross domestic product (GDP) is used as the index for economic activity. If the rate of growth in per capita GDP during the next 45 years (*e*) is set at approximately 1-2% and the rate of change in population (*f*) is set at -0.5% per year (the latest middle estimate of National Institute of Population and Social Security Research), then due to the aforementioned relationship, the identity becomes $-3.7 > b+c+d+1\sim2-0.5+g$, and with b and $g = 0$, $c + d < -5.2\sim-4.2$ (% per year). In other words, on the two-dimensional plane of energy intensity and carbon intensity changes shown in Figure 6, the lower left-hand side of the -45° line passing through the center of the plane from upper left to lower right is the domain in which the 80% reduction target is achieved. Japan's results for the past 40 years and the past 10 years are near the ○ location in the upper right-hand section, therefore $c + d$ is approximately -1% per year. In other words, in addition to the reduction speed up to now, it will be necessary to accelerate the rate of change by around 3-4% per year. In order to achieve this objective, drastic reforms will be needed for both energy supply and demand in the next 45 years. This will involve implementing significant improvements in energy efficiency and socio-economic efficiency[9] and quadrupling macroscopic energy efficiency (equivalent to the speed of improvement of energy intensity at 3% per year, or the reduction of primary energy to approximately 50% by 2050), while at the same time using compelling policies to introduce carbon-neutral energy to cut carbon intensity in half (that is, by improving carbon intensity by 1.5% per year).

European nations plan to implement similar measures. However, while this kind of major transformation of energy systems is being planned, there are also plans that anticipate reducing the speed of reduction by 1-2% per year (b = -1～-2% per year) through the introduction of carbon dioxide capture and storage. The speed of transformation of socioeconomic systems needed for atmospheric stabilization is of a scale unprecedented in history, and reaffirms the severity of the global restrictions that have been imposed in the first half of the 21st century and the challenging efforts that are needed.

Conclusion

This study has reviewed the research into the level of dangerous climate change and has studied the degree of greenhouse gas reductions necessary to avoid reaching this level. The results can be summarized as follows.

1. With regard to the level of dangerous climate change, there has been a great deal of discussion and research since the Villach and Bellagio conferences of the 1980s.[10] At the very least, we are beginning to see a convergence of the debate on the view that an increase in global mean temperature of more than 2°C on pre-industrial levels will have serious consequences.

2. The objective of the United Nations Framework Convention on Climate Change is to stabilize atmospheric concentrations. From the standpoint of controlling climate change, it is appropriate to use a parameter value in which all the causes of climate change are concentrated as the indicator of atmospheric concentration (RF equivalent concentration). The EU uses the GHG concentration value, which only covers Kyoto gases, as an indicator. This value is normally several dozen ppm higher than the RF equivalent concentration.

3. In order to restrain the increase in global mean temperature to 2°C or less on

pre-industrial levels, the target concentration (RF equivalent concentration) must be made approximately less than 475 ppm. This is equivalent to a Kyoto gas concentration of approximately 500 ppm. The temperature rise for a target of 550 ppm for Kyoto gas concentration will change year by year, but it will be approximately 2.5°C by 2150.

4. These temperature increases will change depending on the climate sensitivity. The aforementioned estimation is for a climate sensitivity of 2.6°C. Considering the uncertainty of climate sensitivity mentioned by the IPCC, there is an approximate 10% probability that, for a target of 475 ppm, the long-term rise in global mean temperature will exceed 3°C on pre-industrial levels. The probability is approximately 50% in the case of 2°C and 98% in the case of 1°C.

5. When emissions are reduced using the 475 ppm target, the rate of change in global mean temperature will reach the maximum value (0.24°C per decade) around 2020 but will fall to 0.2°C per decade or below by 2030 and will decrease thereafter. With regard to the danger level for the rate of temperature change, there are still many unknowns but, up to now, values of 0.1-0.2°C per decade have been proposed.

6. If the target concentration is set to 475 ppm, worldwide Kyoto gas emissions should be reduced to 60% of 1990 levels by 2050. Even if the time preference and technical progress settings are changed, there will be little change in this value.

7. Kyoto gas emissions per capita in 2050 for a target of 475 ppm will be 0.6 tCeq per year. If this value is used to assess reduction targets for Japan, the emission allowance in 2050 will be approximately 20% (an 80% reduction) as compared with 1990 levels. The introduction of emissions trading and carbon dioxide capture/storage methods can help lower this target, but careful study will be needed to determine the appropriate degree of introduction.

8. In order to meet the target of an 80% reduction, drastic transformations of the energy supply and demand system will be needed over the next 45 years. Future study will need to determine what changes in energy efficiency and the energy mix will be appropriate. However, to give one example, the target can be achieved by quadrupling existing energy efficiency and cutting carbon intensity in half.

Notes

[1] In the past, the IPCC has advocated a range of 1.5-4.5°C for the value of climate change. In its Third Assessment Report (IPCC, 2001a), a range of 1.7-4.2°C, derived from seven climate models, was revised as the value for climate sensitivity used for future projections. My article uses 2.6 °C as the value for climate sensitivity. This is not only the median value of the seven climate sensitivity values determined by the models used in the Third Assessment Report, but is also the median value for the log-normal distribution with 1.5-4.5°C as the 90% confidence interval.

[2] Time preference relates to people's preference to enjoy benefit in the present rather than to delay it into the future. The rate of time preference is the rate at which the present value of utility declines as the time at which it is enjoyed moves further into the future (Markandya et al. 2001).

[3] The Kyoto gases are: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF6). The model proposed by Hijioka et al. uses nine main types of HFCs and three main types of PFCs in its analysis.

[4] In this study, the main causes of climate change are considered to be Kyoto gases as well as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), tropospheric ozone, the direct and indirect effect of aerosols (sulfate aerosols, black carbon, organic carbon), changes in solar radiation, and albedo changes resulting from changes in land use.

[5] The following relationship exists between the target concentration (C, RF equivalent concentration) and the long-term change in global mean temperature (ΔT_{equiv}).

$$\Delta T_{equiv} = \Delta T_{2\times CO2} \log_2\left(\frac{C}{C_0}\right)$$

where ΔT_{2XCO2}: climate sensitivity, C_0: pre-industrial CO_2 concentration (280 ppm). The target concentration that will ensure $\Delta T_{equiv} = 2°C$ when these values are used is 477 ppm.

[6] The 90% confidence interval for climate sensitivity was set between 1.5-4.5°C. It is assumed to have a log-normal distribution.

[7] $a = b + c + d + e + f + g$, where a: rate of emissions reduction (% per year), b: rate of change in the ratio of carbon capture and sequestration (CO_2 emissions/CO_2 generation), c: rate of change in carbon intensity (CO_2 generation/primary energy), d: rate of change in energy intensity (primary energy/GDP), e: rate of change in per capita GDP, f: rate of change in population, g: confounding term.

[8] Carbon dioxide capture and storage is an emission reduction measure consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere.

[9] The socio-economic efficiency represents an overall energy efficiency of the socio-economic system including the effects of social, economical and cultural obstacles to the use of technologies and creating/accepting the produced utility.

[10] In the 1980s, a series of international workshops were carried out by the International Council of Scientific Unions, the World Meteorological Organization, and the United Nations Environment Program. The International Conference on the Assessment of the Role of Carbon Dioxide and of Other Greenhouse Gases in Climate Variations and Associated Impacts, held at Villach, Austria in October 1985, and further workshops held in Villach and in Bellagio, Italy, in 1987, were famous for their contribution to developing global recognition of the climate change problem.

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Yuzuru Matsuoka is a full professor at the Graduate School of Global Environmental Studies, Kyoto University. He graduated from Kyoto University's sanitary engineering department in 1976 and has more than 30 years' experience as an environmental and sanitary engineer, having worked at the National Institute for Environmental Studies, Nagoya University and Kyoto University. His recent research focuses on the integrated assessment modeling of global environmental issues, particularly climatic change. His Asia Pacific integrated assessment model, known as "AIM", has achieved world renown.